Coupling cyanobacteria dynamics and urban runoff modelling: an integrated approach for a tropical lake in Brazil

Modélisation de la dynamique cyanobactérienne couplée à la modélisation du ruissellement urbain: une approche intégrée pour un lac tropical au Brésil

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RÉSUMÉ

Dans les régions urbaines, l'expansion des surfaces imperméables conduit à une augmentation du volume et de la vitesse d'écoulement des eaux de ruissellement, à l'origine d'une capacité plus importante d'entraînement des polluants, dont les nutriments, vers les milieux récepteurs dont les lacs. Une approche de modélisation intégrée où un modèle hydrologique est couplé à un modèle écologique est proposée pour le lac Pampulha (Brésil) afin d'étudier l'impact des changements du bassin versant sur la dynamique des cyanobactéries. Cet article décrit la méthodologie utilisée pour mettre au point les deux modèles ainsi que pour procéder à leur couplage. Les résultats du modèle pluie-débit ont montré un bon accord avec les mesures, le coefficient de Nash étant compris entre 0.71 et 0.90. Le modèle écologique alimenté par un débit d'entrée calculé par le modèle hydrologique représente correctement l'évolution de la température et des cyanobactéries, les valeurs de l'erreur quadratique moyenne étant respectivement, 0.71°C et 7.20 µg chla L^{-1}. Un nouveau jeu de données permettra de caler le module qualité du modèle hydrologique et de simuler différents scénarios d'évolution du bassin versant.

ABSTRACT

In urban areas the increasing imperviousness is responsible for rising runoff volume and speed, leading to a greater capacity to load nutrients and pollutants into lakes. In order to study the impacts of catchment changes on cyanobacteria dynamics in urban lakes, a modelling approach in which a hydrological model is connected to an ecological lake model is proposed for Lake Pampulha (Brazil). In this paper we present the methodology used to link both models.The results of the rainfall-runoff model show good agreement with measurements, the Nash coefficient ranges between 0.71 and 0.90. The lake ecological model is fed by the runoff water volume calculated by the hydrological model. It successfully represents water temperature and cyanobacteria dynamics. The root mean square error values are respectively, 0.71°C and 7.20 µg chlaL^{-1}. A new dataset which is presently collected will allow us to calibrate the water quality module of the hydrological model and to simulate different scenarios of catchment changes.

KEYWORDS

Cyanobacteria, Ecological modelling, Runoff modelling, Urban lake

1 INTRODUCTION

Estimation of nutrient loading is a key information for environmental management and planning *e.g.* for selecting the best strategies for improving and preserving water quality in receiving freshwaters. Among the many pollutants loaded by the urban runoff, nitrogen and phosphorus are of particular concern for lakes which are especially vulnerable to nutrient enrichment because of their relatively high retention time (Zhang and Jørgensen, 2005). Eutrophication is responsible for decreasing the ecosystem biodiversity and disrupting water uses such as drinking water supply and fishing. Moreover, eutrophic lakes are frequently affected by cyanobacteria blooms, including potential toxic species which can be harmful to human and animal health (Paerl *et al*., 2001).

Cyanobacteria blooms are expected to increase their frequency and intensity in response to climate change and expanding urbanization. Each lake may respond in different ways to the climate change (Tanentzap *et al*., 2008). Although, it is generally expected that global warming will increase primary production in most lakes and favour cyanobacteria blooms by rising water temperature and lengthening its growth period (Paerl and Huisman, 2008). On the other hand, urbanization increases the input of nutrients in water bodies and contributes to accelerate their eutrophication (Zhang and Jørgensen, 2005).

The most reliable method to quantify nutrient loads from runoff is to establish a comprehensive monitoring of the catchment area; however, this is rarely possible due to high costs. Furthermore, when it is necessary to perform prognostic studies, measurements are generally insufficient and modelling approaches are frequently applied (Chow *et al.*, 2012; Wu *et al.,* 2006). Numerical modelling has also been extensively applied to simulate thermal and algal dynamics in lake ecosystems (Huang *at al.*, 2012; Reynolds et al., 2001), especially in view of the complexity of the mechanisms involved in algal growth and in their toxin production.

Despite the strong link between the catchment runoff and the nutrient load into the receiving water body, only recently these processes have been addressed in an integrated way. The link between hydrological and lake modelling consists in using runoff output from the hydrological model as an input for the lake model (Wu *et al.*, 2006; Xu *et al.*, 2007 and Norton *et al.*, 2012). This is necessary for applying different scenarios of catchment changes and for simulating the response of the aquatic ecosystem. Because of the rapid and important evolution of urban areas, namely, extension of urbanization, climate change and increasing concern about water quality, the integrated modelling approach offers numerous possibilities to be explored. Xu *et al.* (2007) and Norton *et al.* (2012) highlighted that such a coupled modelling approach is more easily accepted by managers and by the general public because it can be more readily seen as a representation of a natural linked system.

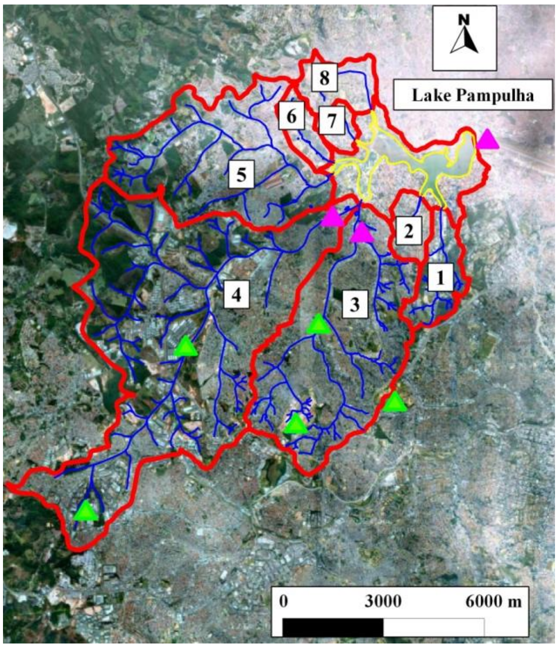
The researches mentioned above have dealt mainly with rural catchments while lakes and reservoirs in urban catchments are understudied. In urbanized areas, the increasing imperviousness rises the runoff volume and velocity, which enhance the nutrient loading into receiving water bodies (Zhang and Jørgensen, 2005). Actually, there is a strong need to investigate the links between the ecological lake functioning and urban catchment changes such as urbanization and improvements or degradation on sewage collection, wastewater treatment facilities and wet weather diffuse pollution control measures. This paper presents a modelling approach in which a hydrological model is connected to an ecological lake model which in a further stage will be applied to study the impacts of future catchment changes on cyanobacteria dynamics in an urban lake in Brazil.

2 MATERIAL AND METHODS

2.1 Study site

Lake Pampulha is a small and hypereutrophic reservoir in Belo Horizonte city, Brazil (19°55'S, 43°56'W, Figure 1). The climate in the region is a tropical mountain climate, with a dry cool season between April and September and a wet hot season from October to March when 90% of the total annual rainfall occurs (mean rainfall = 1 500 $mm.year^{-1}$). Air temperature shows relatively small amplitude over the year with a minimum monthly mean of 18°C in July and a maximum monthly mean of 23°C in February (Nascimento *et al.,* 2006). Lake Pampulha is fed by eight small creeks (Figure 1), Sarandi and Ressaca creeks are the most important (70% of the inflow rate) and also the most polluted ones (Tôrres *et al.*, 2007). The main physical and chemical characteristics of Lake Pampulha are listed in Table 1.
Originally, the reservoir was built to supply drinking water to the city, however, since the 1970s, the water quality has degraded as a consequence of the rapid catchment urbanization with neither

sanitation infrastructure nor erosion control. Nowadays, lake silting and the reduction of its storage capacity, water eutrophication and the consequent increase of primary production with episodes of cyanobacterial blooms and excessive growth of macrophytes are the main problems to be tackled. Despite its poor water quality, Lake Pampulha is an important tourist spot, the area around the lake is used for recreational and sportive activities and it contributes to reduce flood risk in the neighbourhood.



On the left, Lake Pampulha subcatchments: (1) Mergulhão ; (2) Tijuco ; (3) Ressaca ; (4) Sarandi ; (5) Água Funda ; (6) Baraúnas; (7) AABB; (8) Olhos d'água

Figure 1: Lake Pampulha (on the right) and its catchment (on the left). Triangles: green - rainfall stations; pink - rainfall and water level stations; blue – automatic samplers and sensors of temperature and turbidity. Red circles: sampling points in Lake Pampulha (satellite imagery © 2012 Google Earth, © 2012Digital Globe, © 2012 Geoeye)

Table 1 : Lake Pampulha main features

Pampulha Catchment	Population (inhabitants)	~350 000
	Total area (km^2)	98
	Ressaca catchment area (km^2)	20
	Sarandi catchment area (km^2)	49
	Ressaca+Sarandi mean flow dry weather [(1)] (m^3s^{-1})	0.65
	Ressaca+Sarandi mean flow wet weather [(1)] (m^3s^{-1})	1.63
Lake Pampulha[(2)]	Mean depth (m)	5.1
	Maximum depth (m)	16.2
	Area (m^2)	1.97×10^6
	Volume (m^3)	9.9×10^6
Water quality [(3)]	P_{total} (µg P L^{-1})	58 – 925 (207)
	PO_4^{-3} (µg P L^{-1})	1.7 – 113.1 (22.1)
	NH_4 (mg N L^{-1})	1.44 – 14.75 (5.71)
	NO_3 (µg N L^{-1})	3.61 – 460 (82.9)
	Chlorophyll-a (µg L^{-1})	19.5 – 322.0 (113.0)

[(1)] Tôrres et al. (2007), [(2)] Resck et al. (2007), [(3)] Min – Max (Mean value). Monitoring from December 2011 to July 2012 at 0.50 m depth (unpublished data)

2.2 Data collection

2.2.1 Catchment monitoring

Pampulha catchment is monitored by the municipality of Belo Horizonte and within the Stormwater Management Research Project – MAPLU 2. Rainfall data are provided by seven precipitation stations located in or around the catchment (Figure 1). Continuous water level data in Sarandi and Ressaca creeks are measured by two discharge stations installed just upstream their mouth into the lake. Rainfall depths and water levels are automatically measured every 10 minutes since early October 2011. Water quality data are not available for the 2011/2012 rainy season and therefore modelling is still restricted to rainfall-runoff simulations.

By December 2012, sensors have been installed in the Lake Pampulha main inlet and in its outlet (Figure 1) to perform continuous high frequency measurements of water temperature and turbidity. At the same spots, two automatic samplers collect water samples for laboratory analysis (TSS, NH_3, NO_3, P_{tot}, PO_4^{-3}) during rain events. The quality data are currently being acquired.

2.2.2 Lake monitoring

From mid-September to early November 2011, bi-weekly vertical profiles (eleven profiles in total) of water temperature and algal fluorescence were performed with a spectrofluorometer probe in three different points of the lake (Figure 1). Monthly samples were collected under the surface for nitrate, nitrite, ammonium, phosphate and total phosphorus analysis. Since flow measurements in the tributaries were not yet performed, inflows and outflows have been estimated from a water balance based on the measured water level of Lake Pampulha. Inflow water quality (nitrate, phosphate and ammonium concentration) has been assessed since February 2012 by bimonthly punctual sampling. Meteorological variables (solar radiation, wind speed, air temperature and atmospheric pressure) were provided at hourly time step by a weather station of the Brazilian National Institute of Meteorology located 3 km far from the lake.

In Mars 2013, at a central point in the lake (point P2 in Figure 1), a buoy equipped with sensors to measure water temperature, dissolved oxygen concentration, conductivity and algal fluorescence was installed. Measurements are performed every 1 hour and transmitted daily through GPRS to a database. These data are currently under treatment process.

2.3 Modelling approach

2.3.1 Hydrological model

The hydrological model here adopted is the Storm Water Management Model - SWMM 5 (Rossman, 2010), a dynamic rainfall-runoff model that computes flows and associated wet weather non-point pollutant processes. More details about SWMM can be found in Rossman (2010).

Since water levels were measured in two different points, *i.e.* Ressaca and Sarandi streams, these subcatchments were simulated separately while the others have not been simulated yet. Effective precipitation was computed using the Curve Number method and dynamic wave was chosen as the flow routing model. Ressaca subcatchment is entirely in Belo Horizonte territory and detailed cadastre of the drainage network is available. On the opposite, most of the Sarandi catchment is located in Contagem, the neighbouring municipality, and data of the drainage network are not available with the same level of precision, allowing only a rough spatial division of the catchment. Thus Ressaca and Sarandi catchments were divided respectively into 54 and 10 subcatchments according to their topographic features, land use and channel characteristics which were obtained from topographic maps and stormwater network cadastre (Bonnary, 2011). Maps were also used to provide subcatchment information, such as slope or impervious cover. The Thiessen polygon method was applied to spatially distribute rainfall data from the rain gauges.

An automatic model calibration procedure based on a genetic algorithm (Savic and Khu, 2005) was used to calibrate the parameters most difficult to assess, namely: (i) the Manning coefficient of conduits (n-cond),, (ii) the time necessary for a fully saturated soil to completely dry (Dry time), (iii) characteristic width of the overland flow path for sheet flow runoff (w), (iv) Manning coefficient for overland flow over the impervious areas (n-imp), (v) Manning coefficient for overland flow over the pervious areas (n-perv), (vi) depth of depression storage on the impervious areas (s-imp), (vii) depth of depression storage on the pervious areas (s-perv) and (viii) the Curve Number parameter (CN). The optimisation function adopted was Nash criterion (equation 1). To achieve a compromise between model performance and computing time the maximum number of iterations was set equal to 100 for

Ressaca catchment and 50 for Sarandi catchment.

$$Nash = 1 - \frac{\sum_{i=1}^{n}[F_{sim}(i) - F_{mes}(i)]^2}{\sum_{i=1}^{n}[F_{sim}(i) - \overline{F_{mes}})]^2} \qquad \text{Equation 1}$$

Where F_{sim} is the calculated flow at time step *i* (m^3s^{-1}) ; F_{mes} is the observed flow at time step *i* (m^3s^{-1}) and $\overline{Fmes}$ is the mean measured flow over the simulation period (m^3s^{-1}).

2.3.2 Lake ecological model

In lake modelling, hydrodynamic models are frequently coupled to ecological models: the former describes the physical processes of transport and mixing in the water column, while the latter represents the main chemical and biological processes that affect phytoplankton and higher trophic levels. The deterministic model DYRESM-CAEDYM (hereafter DYCD) is used in order to simulate water temperature and cyanobacteria dynamics in Lake Pampulha. DYRESM (DYnamic REServoir Simulation Model) is a one-dimensional hydrodynamic model based on variable depth layers used to predict the vertical distribution of temperature, salinity and density. CAEDYM – (Computational Aquatic Ecosystem Dynamics Model) simulates biological and/or chemical processes such as nutrient cycling and algal succession (Hamilton and Schladow, 1997). The input data are (Figure 2, right hand side block): lake morphometry, inflows (water temperature and nutrient concentrations), outflows, meteorological forcing (wind speed, air temperature, solar radiation, rainfall, cloud cover and vapour pressure) and the initial conditions for cyanobacteria biomass, nutrient and dissolved oxygen concentrations and water temperature.

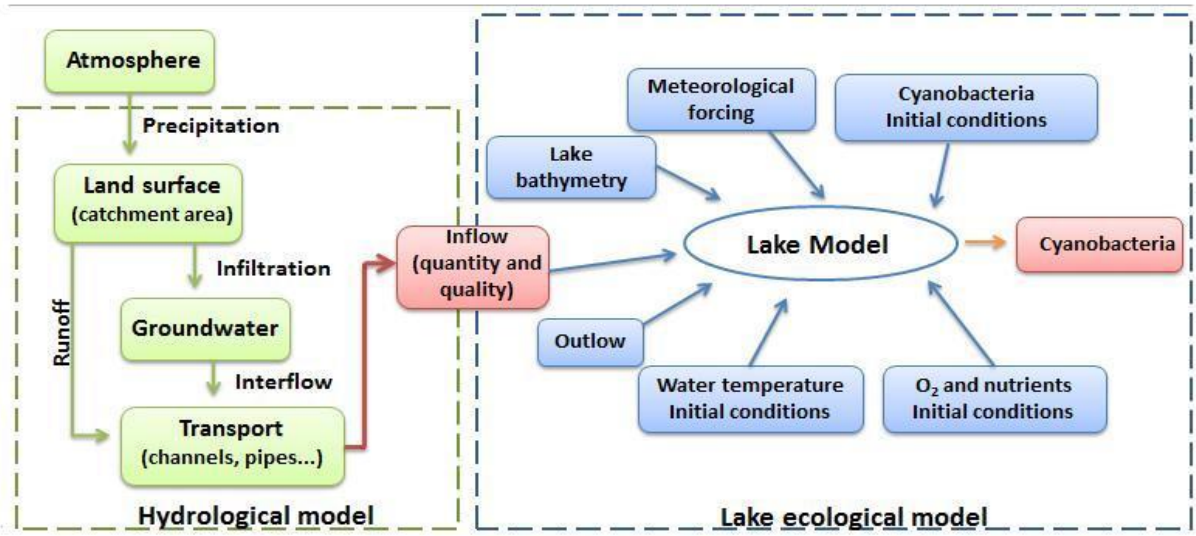


Figure 2 : Integrated modelling diagram: rainfall-runoff model steps and lake model inputs and output.

In the model configuration applied to Lake Pampulha, cyanobacteria are represented by the equivalent chl-a concentration. They are not submitted to vertical movements such as migration, flotation and settling. Zooplankton groups and higher trophic levels are not included in the simulation. Nitrate and phosphate limitations are simulated through the Michaelis-Menten equation. Half-saturation constants for nitrates and phosphates are set to 55 and 5 µg.L^{-1}, respectively. Chl-a concentration was converted into carbon by using a constant rate of 40 mg C.mg $chla^{-1}$. To assess model performance, the root mean squared error (rmse, Equation 2) between measurements and the simulated water temperature and cyanobacteria biomass at each time step and each depth was computed where field data were available.

$$\mathrm{rmse} = \sqrt[2]{\frac{1}{\sum_{i=1}^{m} n_m} \times \sum_{i=1}^{n}\sum_{j=1}^{m_i}\left[\theta_{sim}(t_i, d_j) - \theta_{mes}(t_i, d_j)\right]^2} \qquad \text{Equation 2}$$

Where Θ_{sim} (t_i,d_j) is the water temperature (°C) or the cyanobacteria biomass (µg chla L^{-1}) simulated by the model at time step *i* and depth *j* and Θ_{mes} (t_i, d_j) is the water temperature (°C) or the cyanobacteria biomass (µg chla L^{-1}) measured at time step *i* and depth *j*.

2.3.3 Integrated modelling approach

Once calibrated and validated separately the rainfall-runoff and the lake model are coupled by using the outflow volume and water quality simulated by the hydrological model as input to the lake model, which in turn will simulate cyanobacteria dynamics (Figure 2).

It is expected that this coupled models can be used to assess the impact of different scenarios of catchment changes: (i) meteorological changes such as air temperature increase, changes in rainfall regime and in wind speed; (ii) inflow rate and quality degradation due to the intensification of land-use, the expansion of impervious areas, or in the opposite, improvement of the sanitation network.

As mentioned in paragraph 2.2.2, water quality data from the tributaries of Lake Pampulha are not yet available, only bimonthly sampling was performed in order to estimate the nutrient and suspended solids concentrations entering into the lake. However, an initial simulation of the coupled model was performed by using outflow simulated by SWMM to provide inflow data in DYCD modelling. This first simulation will allow us to check the influence of the simulated discharge on the results of the lake model.

3 RESULTS AND DISCUSSION

3.1 Rainfall-runoff modelling

For both catchments, eight parameters were calibrated (see section 2.3.1). For each catchment, a mean value of the parameters was obtained, except for CN which was calibrated for each subcatchment of Ressaca and Sarandi catchments. The parameters for Sarandi catchment were calibrated with data measured from 18th November 2011 to 13th January 2012 and then validated with data measured between 14th January and 13th March 2012. In a next step, the parameters were calibrated during the latter period and validated over the former one, following a cross-calibration approach. This method allows us to obtain more reliable parameter estimations since the measurements available for calibration correspond to only one rainy season. The same method was applied for Ressaca catchment from 1^{rst} February to 18th March 2012 and from 19th March to 2nd May 2012.

The simulation period of Sarandi catchment encompasses most of the rainy season (total rainfall = 1348.8 mm). Runoff modelling shows good results, with Nash coefficient ranging from 0.74 to 0.90 (Figure 3, Table 2). The model successfully reproduced the flow peak time and intensity (see example in Figure 3). The simulation period of Ressaca catchment encompasses only the end of the rainy season (total rainfall = 339 mm). The performance of the rainfall-runoff model was less effective. However, Nash coefficient values are higher than 0.70 (Table 2), indicating a good agreement between measurements and simulation (Bennis and Crobeddu, 2007). In view of the results obtained for both catchments and taking into account that Sarandi and Ressaca catchments represent respectively 50% and 20% of Lake Pampulha contributing area, the model can be considered calibrated, validated and ready to be coupled to Lake Pampulha model. To take into account the runoff produced by the others ungauged subcatchments, the sum of the daily water volume of Sarandi and Ressaca creeks was increased by 30% according to estimation performed by Tôrres *et al.* (2007).

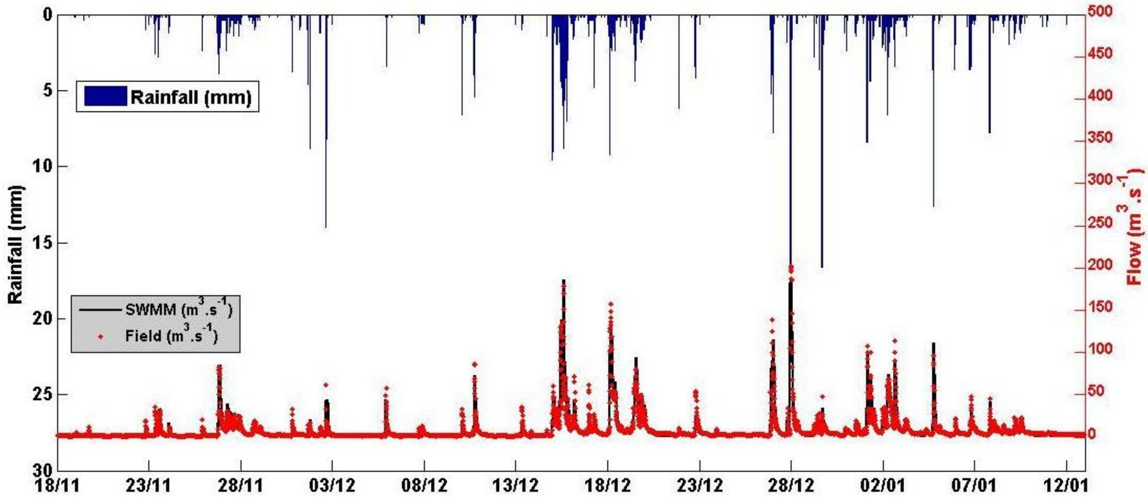


Figure 3 : Hydrological model results (blue line) and measurements (red dots) for Sarandi catchment (calibration period). On the upper axis, rainfall measured at Sarandi creek outlet.

Table 2 : Rainfall-runoff model performance

	Sarandi catchment			Ressaca catchment		
Simulation	**Period (numbers of days)**	**Total rainfall (mm)**	**Nash coefficient**	**Period (numbers of days)**	**Total rainfall (mm)**	**Nash coefficient**
Calibration	18/11/2011 to 13/11/2012 (56)	1134.63	0.90	01/02/2012 to 18/03/2012 (46)	169.65	0.74
Validation	14/01/2012 to 14/03/2012 (60)	214.13	0.74	19/03/2012 to 02/05/2012 (46)	169.79	0.74
Cross-calibration	14/01/2012 to 14/03/2012 (60)	214.13	0.87	19/03/2012 to 02/05/2012 (46)	169.79	0.79
Cross-Validation	18/11/2011 to 13/11/2012 (56)	1134.63	0.79	01/02/2012 to 18/03/2012 (46)	169.65	0.71

3.2 Water temperature and cyanobacteria modelling

The dataset collected in 2011 was used to calibrate DYCD for simulating water temperature and cyanobacteria dynamics from 19th September to 10th November at the deepest point of Lake Pampulha (point P3 in Figure 1). DYCD was manually calibrated by firstly adjusting the layer thickness. Then a multiplier factor of the wind speed was fit for taking into account different wind conditions on the lake and at the weather station. In a next step, the most sensitive parameters of cyanobacteria growth were calibrated (Table 3). A retro-calibration of the layer thickness and the wind factor was then carried out. Parameters related to phosphorus and nitrogen uptake by cyanobacteria were set as the model default values since nutrients are not limiting the algal growth in Lake Pampulha during the simulation period.

Figure 4 shows the measured and simulated vertical profiles of water temperature. The model results show good agreement with measurements for both water temperature (mean rmse = 0.61°C, mean temperature = 21°C) and cyanobacteria biomass (mean rmse = 6.63 µg chl-a L^{-1}, mean biomass = 30 µg chl-a L^{-1}). During the first days, the water column was mixed. After 4th October, as the surface temperature rises, the water column becomes stratified. DYCD model successfully represents this pattern except on 18th October, date when the water jet located near the sampling point stopped. The water jet has an aesthetic function but it also causes water mixing in this lake area.

Figure 5 shows the measured and simulated vertical profiles of cyanobacteria biomass. Cyanobacteria dynamics follows the water temperature trend: vertical distribution is quite homogenous during the first two weeks and the biomass increases from early October as a result of favourable meteorological conditions (high light intensity and water temperature). Limitation functions calculated by the model for phosphorus and nitrogen are always greater than 0.97; this indicates that cyanobacteria growth is not limited by nutrient concentrations. The ecological model was able to catch these variations. Not surprisingly, the model fails to represent cyanobacterial biomass for the week of October 18th when the local conditions of water mixing are changed by the water jet breakdown.

3.3 Preliminary coupled model

The calibrated and validated rainfall-runoff model was used to simulate the runoff volume in Ressaca and Sarandi catchments from 4th October to 10th November 2011. This period corresponds to a part of the calibration period of Lake Pampulha model. The inflow data obtained from the water balance computation were replaced by the runoff model output. In order to assess the coupled model performance, the quality of the lake model results for water temperature and cyanobacteria biomass was checked.

The change in inflow data has led only to a minor degradation of the lake model performance since the vertical profiles of water temperature and cyanobacteria biomass have remained rather unchanged. For water temperature, the mean rmse is 0.71°C and for cyanobacteria biomass, the mean rmse is 7.20 µg chl-a L^{-1}. The lack of significant variation in the results is encouraging about the two model coupling. However, it could also stand for a lack of sensitivity of the lake model to the inflow volume modelled during this period. This “sensitivity” will be the object of further analyses on the coupled model.

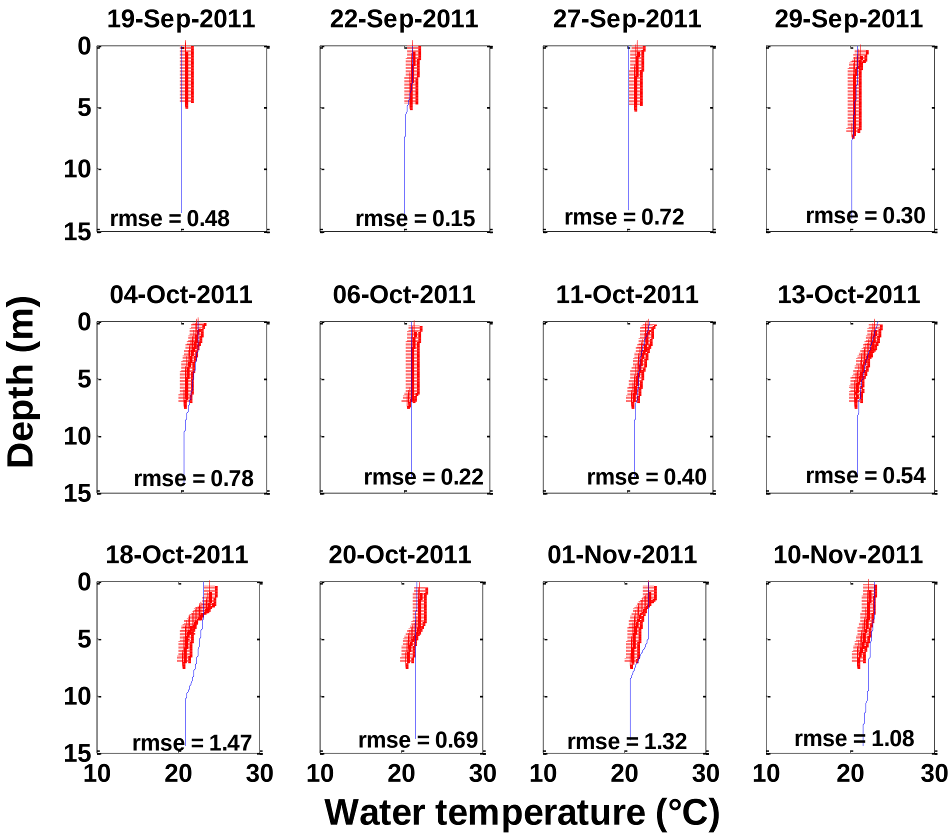


Figure 4 : Model results (thin line) and measurements (thick line) for water temperature at point P3. RMSE values are in °C units

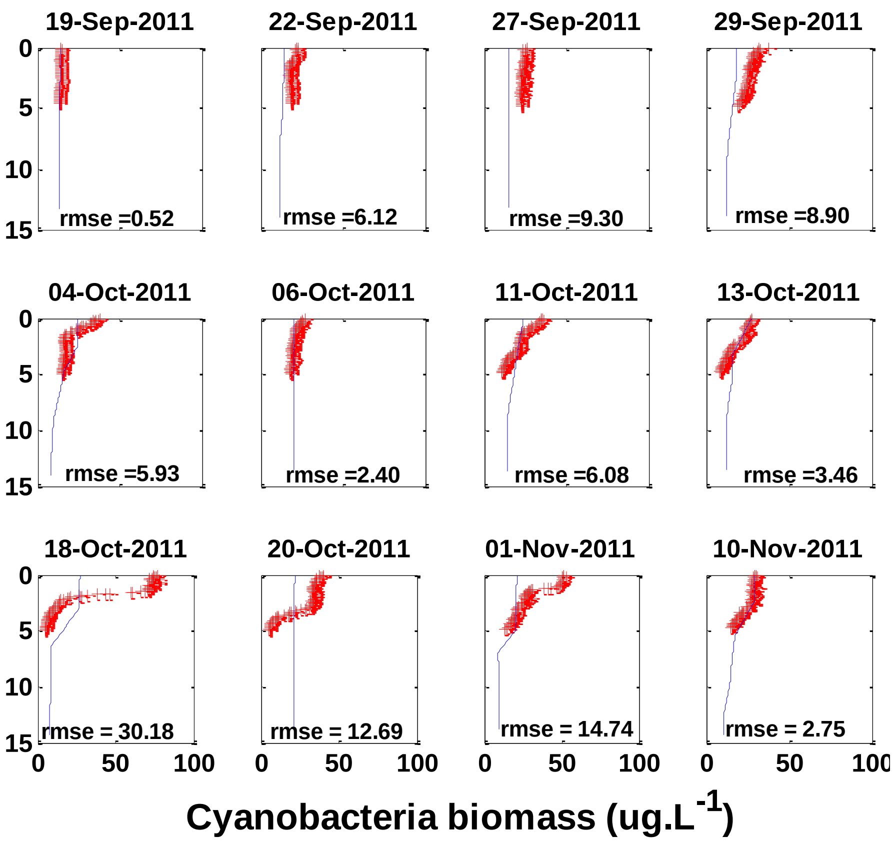


Figure 5 : Model results (thin line) and measurements (thick line) cyanobacteria biomass at point P3. RMSE values are µg chl-a.L^{-1}.

Table 3: Calibrated parameters of the lake ecological model

Parameter	Unit	Range value	Assigned value
Minimum layer thickness	m	0.2 – 1.0	0.6
Maximum layer thickness	m	0.4 – 5.0	4.0
Wind factor	-	1 – 3.0	2.36
Maximum growth rate	day^{-1}	0.5 – 0.7	0.64
Optimum temperature	°C	31 – 33	33
Maximum temperature	°C	39 – 41	39
Light saturation	$\mu Es^{-1}m^{-2}$	100 – 600	290

4 CONCLUSION AND PERSPECTIVES

A coupled modelling is proposed in which the urban runoff simulated by a hydrological model is used as input for a hydrodynamic-ecological model used for simulating cyanobacteria dynamics. Both models, SWMM and DYCD, revealed a good ability to reproduce processes of the water cycle in the urban catchment and into the receiving water body. A first attempt to couple SWMM and DYCD for the moment concerning only water volume is promising. In the next steps, the lake model will be validated with another dataset and the SWMM's water quality block will be used to simulate runoff water quality.

This integrated modelling of the catchment and the lake will make possible to study Lake Pampulha as a water body that integrates and responds to changes occurring in its surroundings. The results obtained will help us to determine in advance the impacts of a likely intensification of urbanization on this water body which has a great touristic, cultural and landscaping relevance to Belo Horizonte city. The assessment of positive impacts resulting from improvements in the sanitation system will be possible and thus management strategies for the lake and its catchment will be likely better conducted. This integrated modelling of Lake Pampulha and its catchment may not only help to define its restoration and protection, but also may be replicated to other water bodies located in urban areas.

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